Defence Science Journal, Vol. 68, No. 3, May 2018, pp. 235-240, DOI : 10.14429/dsj.68.12252

Thermal Design, Analysis and Packaging of an Airborne Multi-output Power Supply Unit

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ABSTRACT

Design of airborne multi-output power supply unit (MOPS) is restricted by space, weight and predefined geometry of air flow path. The unit is cooled by ram air and hence, exposed to the extreme external thermal environment that changes typically from +55°C to -40°C, from ground to cruising altitude within a few minutes. Hence the design should meet the thermal requirements of the electronics inside the packaging adequately, for both the positive and negative extremities of the temperature, so that device limiting temperatures are not exceeded. At the same time, it must accommodate the necessary circuitry. Details of the thermal and mechanical design and performance of the MOPS unit at various altitudes, hot spot location, flow requirements and optimal heat sink design are presented in this paper.

Keywords: Multi output power supply unit; Transmit and receive multi module; TRMM; Antenna system; Power device

NOMENCLATURE

T_{max}	Maximum temperature (°C)
T_{min}	Minimum temperature (°C)
T_{amb}	Ambient temperature (°C)
P_d	Power dissipation (W)
θ	Thermal resistance (°C/W)
LFM	Linear feet per minute
AMSL	Above mean sea level

1. INTRODUCTION

There are standard practices being used by industry in electronics packaging. Major factors considered in designing an electronics enclosure are electromagnetic, mechanical, thermal and thermo-mechanical[1,2]. Mechanical design takes care of housing the electronics from component to enclosure and ability of housing the unit to maintain the integrity under various loading conditions. Thermal design takes care of efficient heat transfer mechanism from the hot spot to the heat sink by selection of suitable cooling mechanism. Whereas thermomechanical factors are concerned with the impact of thermal loads on the mechanical behaviour of the system.

Each electronics packaging is unique and application oriented. Packaging of avionics which are cooled by ram air is always a challenge as they are exposed to harsh environments. Federal Aviation Regulation (FAR), Aeronautical Radio Inc. (ARINC), and Radio Technical Commission for Aeronautics (RTCA), have developed sets of test procedures that help design engineers to test and verify their designs and prevent any failures of avionic systems. However, it is the designer's task to devise an optimal configuration, that meets power and cooling requirements.

Garimella[3], *et al.* have discussed about thermal challenges in the next generation electronic systems. This paper provides inputs on thermal management challenges for next-generation avionics and progress, and challenges in CFD tools. Hung-li[4], *et al.* have investigated experimentally the performance of plate fin heat sinks under cross flow cooling. He has concluded that the thermal performance of plate fin heat sink improves with the increase in the Reynolds number to a certain value and beyond that, it will be limited. He also found that the pressure drop increases with increase in Reynolds number, fin width and fin height. Rao[5], *et al.* have investigated that plate fin heat sink performance is better in flow-through air cooling system compared to impingement-flow cooling system. A l-Sallami[6], *et al.* in their numerical investigations, found that strip fins in staggered arrangement are better in heat transfer.

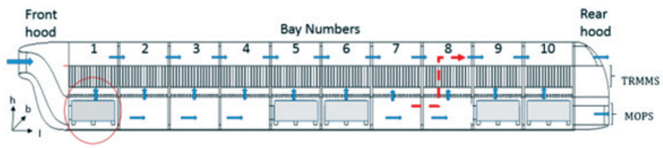
In the present configuration of packaging, heat transfer path is from the base plate of the power electronic device to the casing and then to ram air. This paper focuses on the thermal and mechanical design aspects of the airborne multi-output power supply (MOPS) unit.

2. PROBLEM DEFINITION

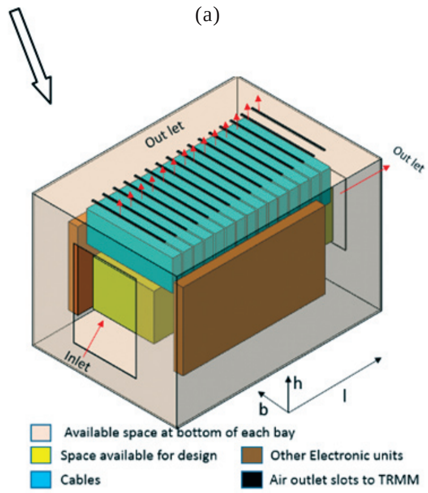
The airborne antennae system is a rectangular box like structure having a duct at the top (top duct), running through its length and a chamber at its bottom (bottom duct), also running through its length. Dimensions of the antennae system are: length (l) 8.2 m, width (b) 0.522 m and height (h) 0.906 m. Transmit and receive multi-modules (TRMMs) are electronic units positioned with a uniform pitch of 6mm at right angles to

Received : 01 November 2017, Revised : 10 March 2018
Accepted : 15 March 2018, Online published : 16 April 2018

both the ducts. This inter spacing between the TRMMs forms airflow channel that links the bottom and top ducts. Air enters the antennae system through the bottom duct, passes through the channels and exits to the atmosphere through the outlet in the top duct. The duct through which the air enters (the bottom duct) is called the distribution manifold and the duct from which the air exits (top duct) is called the collection manifold. This is called a 'reversed Z-type flow configuration' since the direction of the flow from inlet to exit appears like the reversed letter 'Z' which is marked in red arrow in Fig. 1(a).



(a)



(b)

Figure 1. (a) Antennae system and (b) Spatial constraints.

The rectangular portion of the antennae system is divided into 10 equal sections. And each section is called as a bay. The MOPS units, as shown in gray colour in the Fig. 1(a), are housed in the 1st,5th,6th,9th, and 10th bays in the distribution manifold due to accessibility constraints. Due to the reverse Z-flow configuration, flow available in the distribution manifold reduces from 1st bay to 10th bay. Hence, MOPS unit positioned in the 10th bay would receive the least flow compared to the other units. The 3-D view of the distribution manifold (red circled portion at bay-1)is shown in Fig. 1(b). As it is shown in this figure, at any bay, the space available for thermal and mechanical design of MOPS unit is 590mm(l) x 200mm(b)x 150mm(h). Only 51 per cent of space is available for airflow as explained in Table 1.

Table 1. Space studies for MOPS design

Component	Volume (lxbxh)* mm^3	% total volume
Available space at bottom of each bay	674x435x470	100
Other electronics 2 (Numbers)	480x250x300	26.12
Cables (15 groups)	590x200x30	9.3
Space available for design	590x200x150	12.84
% Space available for airflow		51.74

*l-length, b-width, h-height

The base plate of the power device to be packed inside the MOPS has a limiting operating temperature of +100°C (T_{max}) and -40°C (T_{min})[7]. Maximum dissipation of a power device is 70W. Arrangement of the power devices with the heat loads is shown Fig. 2(a) and 2(b). Provision is made for other necessary components like filters and capacitors.

Total dissipation of all MOPS units is 8.5 kW. As the units are positioned in five bays, at each location heat load from these units would be 1.7 kW.

(a)

(b)

Figure 2. Power dissipation details: (a) Slide-1 & (b) Slide-2.

2.1 Operating Environment

The antenna system is operative between the altitudes 5,000 ft and 25,000 ft AMSL. The velocity of the aircraft above which the antennae system is mounted, varies typically between 250 knots to 320 knots. Wind tunnel tests are carried out at Indian Institute of Science, Bengaluru, for 1:2 scaled antennae model to arrive at internal flow details[8]. From the test data, it has been found that the free stream velocity drops to approximately 1/3rd of its value when it reaches the inlet of the front hood. Due to the reduction in velocity, the inlet temperature rises due to adiabatic compression of ram air. This rise is calculated using the formula as follows:

$$\text{Temperature rise} = \frac{v_1^2 - v_2^2}{2c_p}$$

where,

v_1 – free stream velocity of air (m/s)

v_2 – velocity of air at the inlet of front hood of the antenna system (m/s)

c_p - Specific heat of air (1005 J/kg°C)

Table 2 provides the air temperature rise due to adiabatic compression for typical operational altitudes and aircraft velocities .

Table 2. Air Temperature rise due to adiabatic compression

Altitude, (ft)	v_1	v_2 (m/s)	Temperature rise (°C)
5000	250knots (128.6m/s)	43	7.5
25000	320 knots (164.6m/s)	55	12

In India, the highest temperature occurs in the western region of Rajasthan, which is at an altitude of around 1,550 ft, where it can reach up to 50 °C during the day. At 5,000 ft, the ambient temperature in summer would be ~ 45°C. At lowest altitude and at lowest aircraft velocity, the temperature at the entry of the front hood inlet would be 52.5 °C considering the temperature rise due to adiabatic compression. To be on conservative side, 55°C ambient temperature is considered for the analyses.

Similarly, the lowest temperature in India occurs at Drass valley which starts from the base of Zozila pass, the Himalayan gateway to Ladakh. Drass has an altitude of 10,761ft. Here, the average minimum temperature calculated over the years, is about -23 °C [metrological data]. Therefore, at the operational flight height of 25,000 ft, the expected minimum temperature over Drass is -51 °C. For the aircraft velocity of 320 knots, the lowest temperature of the air would be -39 °C, considering the temperature rise due to adiabatic compression.

3. METHODOLOGY

Flow requirements of one power device is arrived from the experimented wind tunnel data. These devices are rearranged as per power requirements within the available space. Preliminary design of enclosure is obtained and the flow requirements are arrived at, with the basic heat sink design. Since the unit is kept parallel to the flow direction, fins of rectangular cross-section are choosen. After obtaining the initial thermal profile, heat sink optimisation studies are carried out. Final design of the packaging unit is done in CATIA. Realised unit integrated with all the electronics is tested for its thermal performance.

4. PRELIMINARY CALCULATIONS

Power device is tested in the wind tunnel by the device manufacturer as per the JEDEC standard[9]. The tested values for different heat sink height for one power device are presented in Fig. 3. To get the basic flow requirements at lower resistances, these curves are extrapolated.

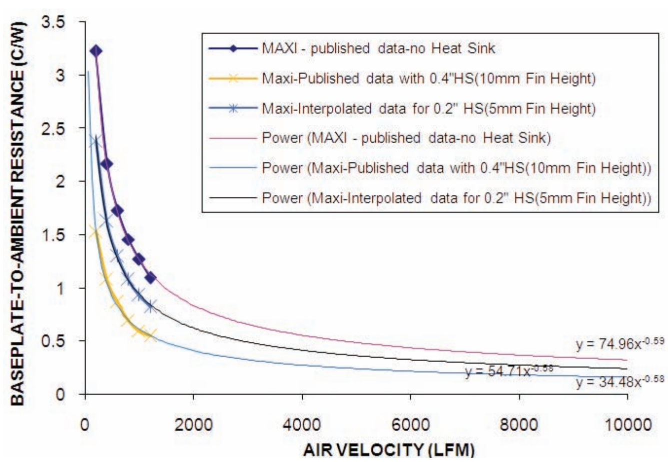


Figure 3. Vicor power device wind tunnel test results.

4.1 Flow Requirement for One Power Device without Heat Sink

Since the limiting temperature of the base plate of power device is 100 °C, a margin of 15 °C is considered and T_{max} is set to 85 °C.

At max ambient temperature(T_{amb}):55 °C,

$$\theta_{base-air} = \frac{T_{\max} - T_{amb}}{P_d} = \frac{85-55}{70} \sim 0.43^0 C/W$$

Corresponding to this resistance, required air flow velocity is 6137 LFM ~32m/s approximately.

4.2 Flow Requirements with Heat Sink

In order to maintain T_{max} 85 °C, with minimum airflow velocity, a heat sink, having a fin height of 10mm (0.4") is selected based on Fig. 3. and the required flow rate would be ~1804 LFM (9.2 m/s). Similarly, for different ambient temperatures, thermal resistances are calculated and corresponding flow requirement for a single power device is arrived at. The details are presented in the Table 3.

Table 3. Air velocity requirements at T_{max}: 85 °C

	T_{amb} (°C)	$\theta_{base-air}$ (°C/W)	Velocity required	
			LFM	m/s
Without heat sink	55	0.43	6137	31.2
With 0.4″ heat sink	55	0.43	1804	9.2
	40	0.64	914	4.6
	30	0.79	637	3.2
	20	0.93	482.2	2.45

Due to the arrangement of power devices in tandem, temperature of available air increases as heat gets added in the flow direction. Hence a flow velocity greater than the estimated velocity (9.2 m/s) is required to cool all the devices. In order to determine an optimal fin arrangement, analyses are carried out with a flow velocity of 10m/s for various fin configurations.

4.3 Preliminary Modelling

Due to the spatial constraints and to ensure good convective heat transfer for all power devices, two MOPS units are arranged in twin tower fashion (Fig. 4), with interspacing of 15 mm for air flow to enable heat transfer through forced convection.

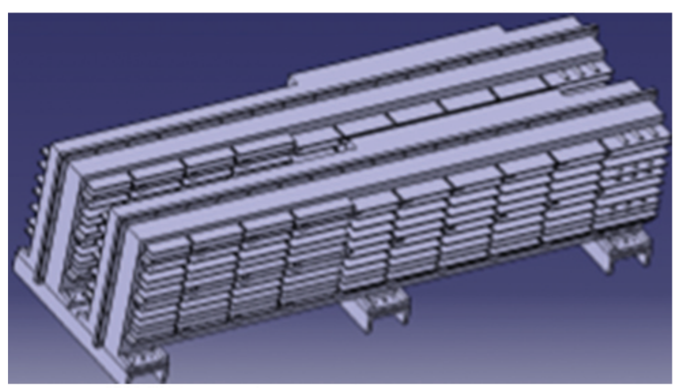


Figure 4. Twin tower arrangement.

Flotherm model that simulates the actual volume representing other electronics and cables is used for conjugate heat transfer analysis.

Inputs for the analysis:

Total heat dissipation for one unit: 850 W

Air flow through each top slot: 25CFM (minimum requirement for TRMM cooling)
Slots dimensions : 6mm(b)x 162mm (l)
Outflow dimensions: 100mm x 100mm
Material of the MOPS unit: Al 6061
Contact resistance between the power device base plate and enclosure: 0.08 °C/W[7]
Analyses are carried out for 55° C and 35 °C ambient conditions. Air properties are taken accordingly.
Boundary conditions:
- Inlet: Fixed flow
- Outlet: Fixed flow (through slots)
- Analysis: Steady-state
- Model: Level K-Epsilon turbulence model
- Grid: 1.5 million cells

4.4 Heat Sink Optimisation

Thermal boundary layer development across the height of the duct is plotted across fin height. From the Fig. 5, it is observed that, beyond a fin height of 20 mm, variation in the air temperature is not significant.

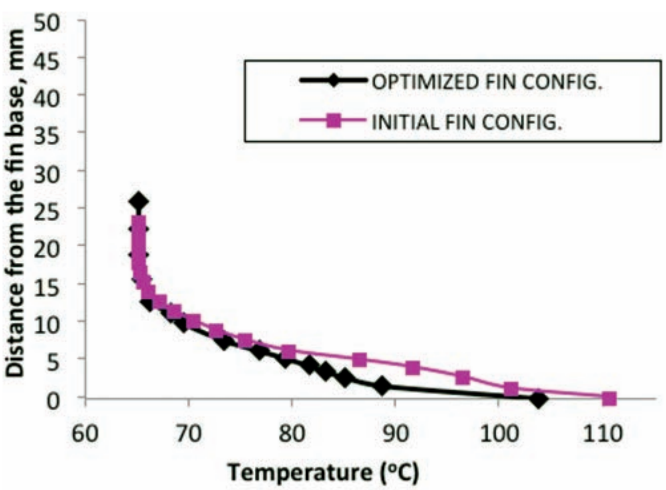


Figure 5. Thermal boundary layer for initial and optimised (staggered fin) configuration.

Hence minimum fin height for the thermal analysis is chosen as 15 mm and hot spot locations are arrived at. It is also observed that thermal boundary layer is predominant at the center portion of the unit. Hence, staggered arrangement of fins is chosen and analyses are repeated. Details of the fin studies carried out and the results are presented in Table 4.

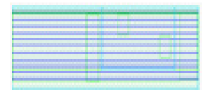
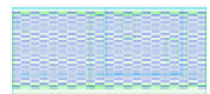
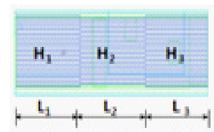
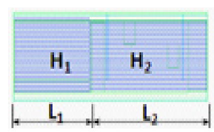
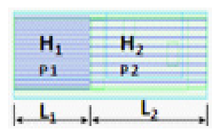
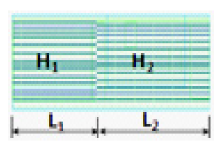
Though configurations 4 and 6 presented in Table 4 are having T_{max} as 102 °C, 6th configuration is considered due to manufacturing and mounting aspects of the power devices. A comparison of thermal boundary layer across fin height for initial configuration and optimised configuration are shown in Fig. 5. It is observed that, in optimised staggered fin configuration, for same fin height, boundary layer height is reduced due to increase in the convective heat transfer.

The external configuration of one MOPS unit is shown in Fig. 6.

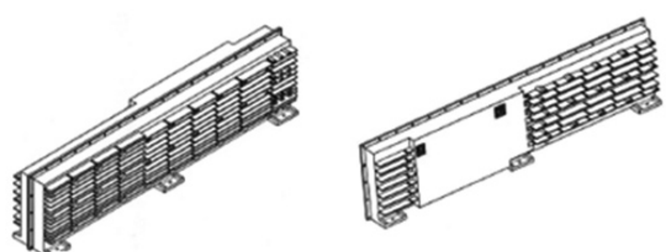
From internal flow studies of the full antennae system, it is observed that the air velocity available in 10th bay would be 20 m/s and maximum velocity available in 1st bay would be 29 m/s for lowest forward speed of aircraft[10]. Hence, conjugate heat transfer analysis is repeated for 20 m/s airflow velocity at 55°C ambient conditions for 6th configuration. Temperature profiles are presented in the Fig. 7 (a) and 7(b) on both sides of the MOPS unit for this configuration.

Grid independent studies are carried out for all the cases and the results of the final (6th) configuration is plotted in Fig. 8.

Table 4. Fin configurations analysed

	Fin arrangement	Fin details (mm)	V (m/s)	T_{amb} (°C)	T_{max} (°C)
1.		N: 11, L: 583 H:15 p: 9 &11	10	35	122
2.		Nx: 21, Ny: 15 L: 25, H: 15 px: 31, py: 6.3	10	35	113
3.		N1: 17, L1: 195 N2: 16, L2: 198 N3: 17, L3: 190 p: 5	10	35	110
4.		N1: 17, L1: 195 H1: 15 N2: 16, L2: 388 H2: 20 p: 5	10	35	102
5.		N1: 17, L1: 195 H1: 15, p1: 5 N2: 16, L2: 388 H2: 20, p2: 10	10	35	106
6.		H1: 15, L1: 195 H2: 17.5, L2: 388 N: 134 fins of 54 width 14 fins of 25 width	10	35	102

Note: p-fin pitch, H-fin height, L-fin length, Nx-No. of fins in x-direction, Ny-No of fins in y-direction

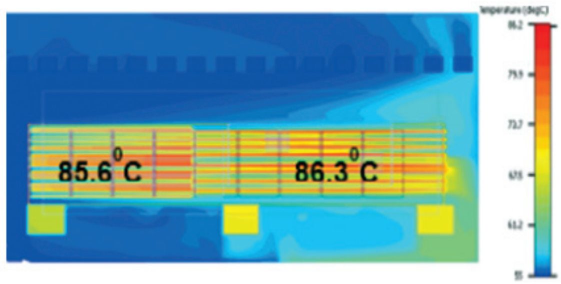


(a) (b)

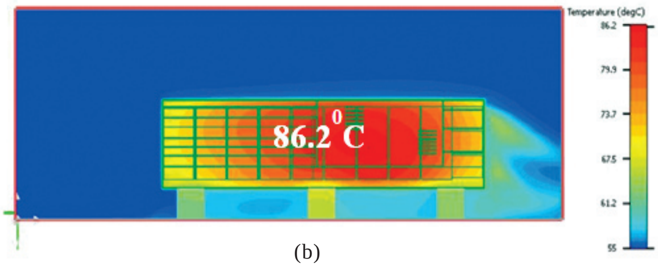
Figure 6. External configuration of one MOPS unit: (a) Side-1 and (b) Side-2.

5. ALTITUDE STUDIES

Analyses are carried out for MOPS unit at different



(a)



(b)

Figure 7. (a) Temperature profile: (a) Slide-1 & (b) Slide-2.

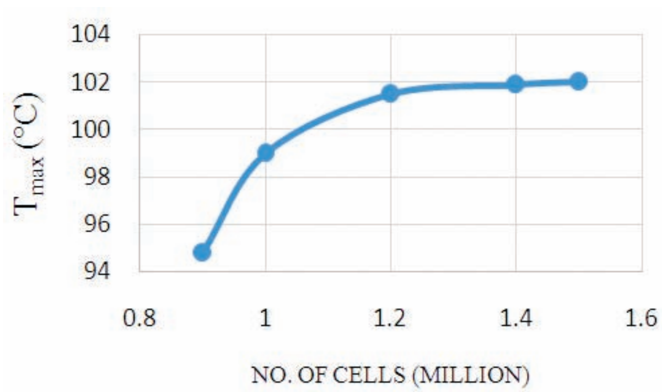


Figure 8. Grid independence check.

altitudes for final fin configuration, and the results are obtained. Figure 9 presents altitude vs. Maximum base plate temperature of the power device. Air properties for the analyses are taken as per IRA conditions. Maximum velocity and minimum negative temperature encountered by MOPS unit at 25000ft altitude at 1st bay are 36 m/s and -39°C (for highest forward speed of aircraft) respectively. At these conditions, maximum temperature at the base plate of the power device is 27 °C.

6. MOPS PACKAGING

MOPS unit of size 590mm x147 mm x 90mm is realised with optimised fin configuration. Necessary EMI sealing is incorporated to the unit and O-ring is provided throughout the circumference to protect the unit from condensation due to varied humid environmental conditions. Each unit casing weighs 2.5 kg and is integrated with the power devices and necessary circuits. Each integrated unit weighs 8.54 kg.

7. EXPERIMENTATION

The test setup for the MOPS performance evaluation

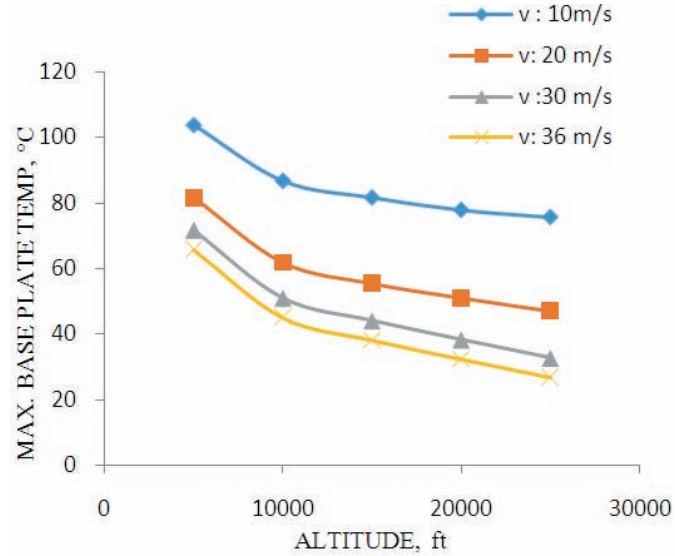
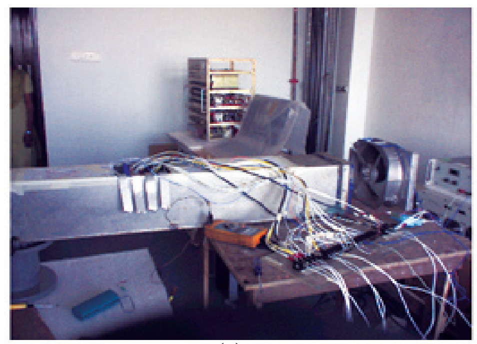
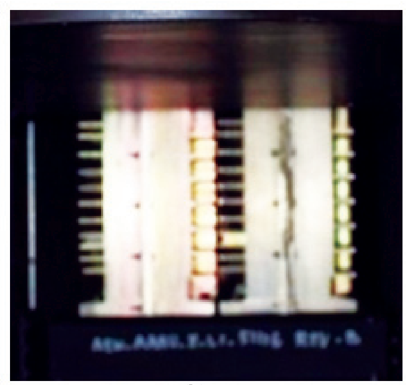


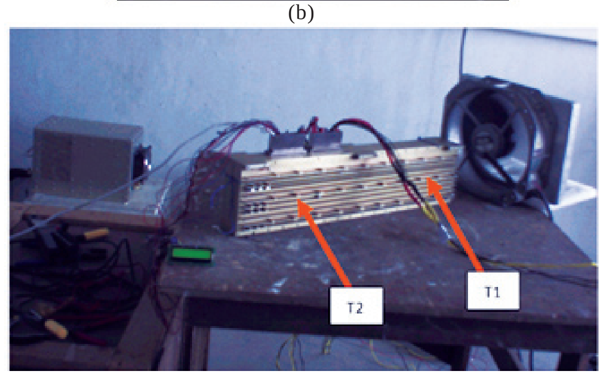
Figure 9. MOPS altitude studies.



(a)



(b)



(c)

Figure 10. (a) MOPS test setup, (b) MOPS arrangement in the duct, and (c) MOPS units without duct.

is shown in Fig. 10(a). The twin tower arrangement of two MOPS units with interspacing of 15 mm is shown in Fig. 10(b). Thermocouples are attached at the locations where the high power devices are located. Figure 10(c) shows location of thermocouples during testing.

Test results compared with analysis results are presented in Table 5. It is seen that there is a maximum deviation of 4 per cent between the two.

Table 5. Analysis *vs* experimental data

Parameter	Air velocity (m/s)	$T_{amb,}$ (°C)	$T_{surface}$ (°C)			
			T1	T2	T3	T4
Analysis	10	37	65.4	71	66	70.1
Experiment	10	37	63.2	68	64	69.5

8. CONCLUSIONS

Thermal design of MOPS unit is carried out within the given spatial and weight constraints. It is seen that for highest forward speed of aircraft (320 knots), at highest flying altitude (25,000 ft) at which antenna system is operative, ambient temperature inside the antennae would be-39 °C, and the power device temperature would be 27 °C, which is well below the specified minimum temperature (-40 °C) limits. So the unit is thermally safe at extreme cold conditions. For lowest forward speed of aircraft (250 knots), at lowest flying altitude (5,000 ft) at which antenna system is operative, the obtained maximum device base plate temperature is 86.3 °C. This value is well within the specified maximum device base plate temperature (+100 °C). Hence, it is concluded that, MOPS unit can be safely operated in the entire flight envelope.

MOPS unit has undergone all qualification and environmental screening tests and certified as airborne. Required number of units are realised, mounted inside the antennae system which is mounted on the top of the surveillance aircraft. During the ground functional trials, the electronics are cooled using ground cooling equipment. The antenna system mounted on the aircraft has undergone several sorties and MOPS units are performing successfully.

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ACKNOWLEDGEMENTS

Authors would like to thank Mr M.S. Easwaran, Director, CABS and Dr S. Christopher, Chairman and Secretary DDR&D, for their support and valuable technical inputs. The authors extend their gratitude to Dr S.K. Venkatesh, for support in conducting the experiments.

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Her contributions to the present work are fin optimisation studies, altitude studies, thermal analysis and validation.

Mr P. Vikram received his BTech (Mechanical Engineering) from Pondicherry Engineering College, in 2001 and ME (Aeronautical Engineering) from Madras Institute of Technology, Chennai, Tamil Nadu, in 2003. Presently he is working as Scientist at DRDO-Centre for Air Borne Systems, Bengaluru. His areas of interest are thermal design and analysis.
His contributions to the present work are 3-D modelling, establishing the test set-up and testing.

Ms Suma Varughese received her MS(Engineering) from Indian Institute of Science, Bengaluru, in 2000. Presently she is working as Scientist and Program Director of Indian AEW&C system at DRDO-Centre for Air Borne Systems, Bengaluru.
Her contributions to the present work are to provide overall guidance to the team.